AFRL-OSR-VA-TR-2015-0102

EXPLORING ELECTRICAL AND MAGNETIC RESONANCES

BIN HU
UNIVERSITY OF TENNESSEE KNOXVILLE TN

04/29/2015
Final Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTD
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
01/03/2015	Final report	July 01 2011 - December 31 2014

4. TITLE AND SUBTITLE

Project title: Exploring Electrical and Magnetic Resonances from Coherently Correlated Long-Lived Radical Pairs towards Development of Negative Refractive-Index Materials

Subtitle:

Task 1: Radicals Based Molecular Metamaterials

Task 2: Thin-Film Based Polymer Thermoelectric Devices

5a. CONTRACT NUMBER

5b. GRANT NUMBER

FA9550-11-0082

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

PI: Bin Hu

Participants: Dr. Lei He, Dr. Dehua Hu, PhD student: Liang Yan, PhD student: Mingxing Li, Ph.D student: Huidong Zang, Ph.D student: Qing Liu

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

University of Tennessee

Department of Materials Science and Engineering

1508 Middle Drive

Knoxville, TN 37996

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Office of Scientific Research

875 N. Randolph Street, room 3112

Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION A

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The research efforts have made following major breakthroughs:

1. Developed new strategy to couple pi-d electrons for the development of molecular metamaterials [J. Am. Chem. Soc. 134, 3549, 2012]
2. Explored new mechanism to utilize intermolecular excited states for realizing electric-magnetic coupling towards developing molecular metamaterials [Adv. Mater. 23, 2216, 2011]
3. Developed new method to use radicals for electric-magnetic coupling towards radicals-based metamaterials [Adv. Mater 26, 3956, 2014]
4. Discovered a novel mechanism to generate magneto-optic properties by establishing spin-exchange interaction in electron-hole pairs in ferroelectrically semiconducting materials [Advanced Materials, DOI: 10.1002/adma.201405946, 2015]
5. Developing new strategy to separately control electrical and thermal conductivities by using interfacial polarization [Adv. Mater. 23, 4120, 2011]

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)*

Reset

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE. State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATES COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. TITLE. Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. CONTRACT NUMBER. Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

5b. GRANT NUMBER. Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

5c. PROGRAM ELEMENT NUMBER. Enter all program element numbers as they appear in the report, e.g. 61101A.

5d. PROJECT NUMBER. Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. SPONSOR/MONITOR'S ACRONYM(S). Enter, if available, e.g. BRL, ARDEC, NADC.

11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/ monitoring agency, if available, e.g. BRL-TR-829; -215.

12. DISTRIBUTION/AVAILABILITY STATEMENT. Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. SUPPLEMENTARY NOTES. Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

16. SECURITY CLASSIFICATION. Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. LIMITATION OF ABSTRACT. This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

Final Report

July 01, 2011 – December 31, 2014

Project title:

Exploring Electric and Magnetic Resonances from Coherently Correlated Long-Lived Radical Pairs towards Development of Negative-Index Materials

Principle Investigator:

Bin Hu

Institution:

University of Tennessee

Address:

Department of Materials Science and Engineering
University of Tennessee
Knoxville, TN 37996
1508 Middle Drive
Email: bhu@utk.edu
Phone: 865-974-3946
Fax: 865-974-4115

Agreement Number:

FA9550-11-1-0082

Objectives:

This project has two objectives: (i) exploring electric and magnetic responses from spin radical pairs to develop molecular metamaterials and (ii) investigating new mechanisms to control the co-operative relationships between key thermoelectric parameters for developing high thermoelectric effects based on hybrid metal/polymer/metal thin-film devices.

Status of Effort:

The research efforts have made following major breakthroughs on molecular metamaterials by using spin radicals and on thermoelectric effects by using polymer/metal interface-controllable thermal and electric conductions.

1. Developed new strategy to couple semiconducting π electrons and magnetic d electrons for the development of molecular metamaterials [*J. Am. Chem. Soc.* 134, 3549-3554, 2012]

   The project has developed a new strategy for coupling semiconducting π electrons and magnetic d electrons by combining optically-generated intermolecular excited states with surface-modified magnetic nanoparticles. This new strategy can lead to optically-controllable composite metamaterials.

2. Explored new mechanism to utilize intermolecular excited states for realizing electric-magnetic coupling towards developing molecular metamaterials [*Adv. Mater*. **23**, 2216-2220, 2011]

   The project has developed a new mechanism for realizing electric-magnetic coupling by using optically-generated intermolecular excited states in organic semiconducting materials. This new mechanism can generate optically-controllable molecular metamaterials.

3. Developed new method to use spin radicals for realizing electric-magnetic coupling towards radicals-based metamaterials [*Adv. Mater* **26**, 3956-3961, 2014]

   The project has introduced spin radicals into organic semiconducting materials for the development of radicals-based metamaterials. This new method can develop spin-tunable electric-magnetic coupling for development of radicals-based metamaterials.

4. Discovered a novel mechanism to generate magneto-optic properties by establishing spin-exchange interaction in electron-hole pairs in ferroelectrically semiconducting materials [*Advanced Materials*, DOI: 10.1002/adma.201405946, 2015]

   The project has discovered a novel mechanism to generate magneto-optic properties by establishing spin-exchange interaction in ferroelectrically semiconducting perovskites. This new mechanism leads to a breakthrough to create magneto-optic functions in all functional materials.

5. Developing new strategy to separately control electrical and thermal conductivities by using interfacial polarization [*Adv. Mater.* 23, 4120-4124, 2011]

   The project explored a new strategy by using interfacial polarization to address the challenging issue: separate controlling on electric and thermal conductions. This new strategy can lead to a significant enhancement on Seebeck effect.

Accomplishments/New Findings:

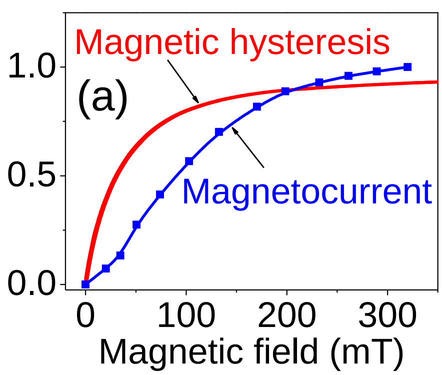
I. Radicals-based molecular metamaterials

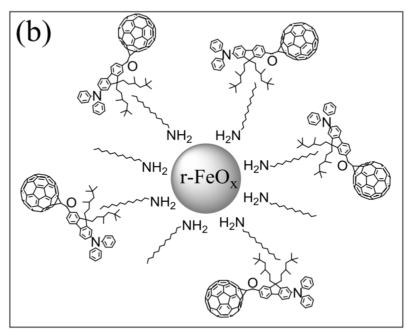
This research task has made the following five accomplishments including:

1. Discovery: new mechanism to realize electric-magnetic coupling by using π-d electron coupling for the development of molecular metamaterials

◆ **Electric-magnetic coupling from organic-magnetic nano-composite in ground state** [*J. Am. Chem. Soc.* 134, 3549-3554, 2012]

We found that a significant electric-magnetic coupling between charge-transfer states, and spin dipoles in ground state can be realized when intermolecular charge-transfer complexes are combined with soluble surface-modified magnetic nanoparticales through nano-composite design. Fig. 1 shows a very interesting magnetocurrent phenomenon that consists three components related to organic semiconducting molecules, magnetic nanoparticles, and a coupling between semiconducting molecules and magnetic nanoparticles. Clearly, this interesting magnetocurrent phenomenon implies that combining intermolecular charge-transfer complexes with magnetic d electrons leads to a new strategy to generate an electric-magnetic coupling in ground state.





Semiconducting-magnetic nano-composite

Fig. 1 (a) Magnetocurrent to show semiconducting, magnetic, and semiconducting-magnetic components. (b) Chemical structure of semiconducting-magnetic nano-composite to show π-d electron coupling.

◆ **Enhanced electric-magnetic coupling from organic-magnetic nano-composite in excited state metamaterials** [Submitted to *Advanced Electronic Materials*]**.**

We found that a stronger electric-magnetic coupling between charge-transfer states and spin dipoles in electric-magnetic nano-composite can be realized when exciting the nano-composite into excited state. Fig. 2 shows an obvious enhanced amplitude and a line-shape change of

magnetocapacitance in excited state from electric-magnetic nano-composite. Apparently, this striking mangetocapacitance change suggests that photoexcitation provide a new method to enlarge the electric-magnetic coupling between charge-transfer states and spin dipoles in the electric-magnetic nano-composite in excited state.

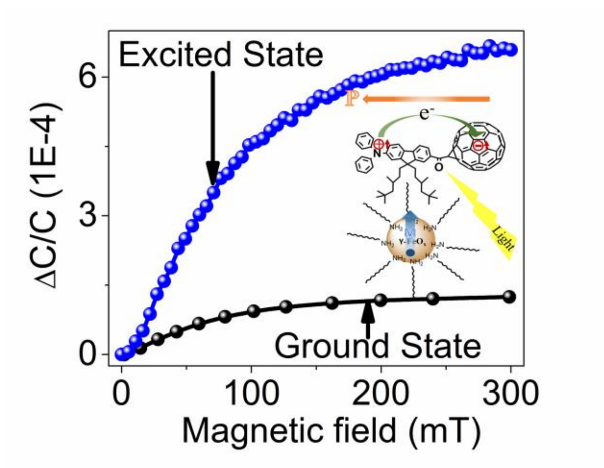


Fig. 2 Magnetocapacitance to show the larger electric-magnetic coupling in excited state.

- **Electric-magnetic coupling from radical pairs in organic molecules** [*Adv. Mater* **26**, 3956-3961, 2014].

We have discovered a new mechanism to generate electric-magnetic coupling by using radical pairs in organic semiconducting donor:acceptor systems. We can see in Fig. 3 that a pure semiconducting donor:acceptor (BBOT:TPD) demonstrates a significant magneto-dielectric function under photoexcitation: a magnetic field can change capacitance in organic semiconducting materials under photoexcitation. This magneto-dielectric function indicates a significant electric-magnetic coupling. Therefore, radical pairs present a new mechanism to generate electric-magnetic coupling towards the development of molecular metamaterials.

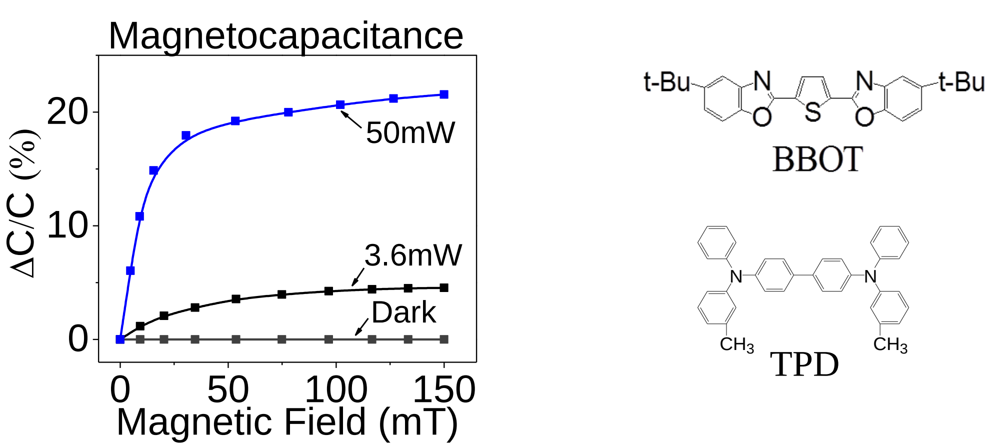


Fig. 3 Magnetocapacitance from optically-generated intermolecular excited states in semiconducting donor:acceptor (BBOT:TPD) composite.

2. New approach: Optically controlling magnetic properties by using charge-transfer states

◆ **Optically tunable magnetic properties through the interaction between intermolecular charge-transfer states** [*Adv. Mater* **26**, 3956-3961, 2014; *Physical Review B* 89, 155304 (2014)].

We have found that the spin-exchange energy in intermolecular charge-transfer states can be manipulated by the photoexcitation through changing the Coulomb interaction spin interaction among the intermolecular charge-transfer states. Fig. 4 indicates that the magnitude and line-shape of magnetocapacitance and magnetophotoluminescence can be changed by increasing the photoexcitation. Consequently, the line-shape narrowing of magnetocapacitance and magnetophotoluminescence illustrates a new way to tune the magnetic properties by photoexcitation through the interaction between intermolecular charge-transfer states, leading a new method to realize the molecular metamaterials.

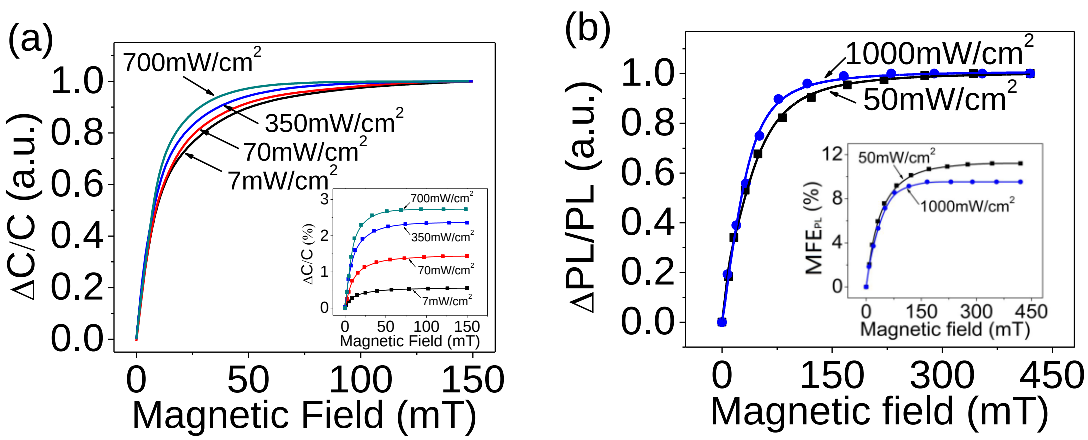


Fig. 4 (a) Magnetocapacitance in semiconducting donor:acceptor (BBOT:TPD) composite under different photoexcitation intensities. (b) Magnetophotoluminescence in semiconducting donor:acceptor (Pyrene:DMA) in DMF under different photoexcitation intensities.

◆ **Optically tunable magnetic properties through the interaction between intermolecular charge-transfer states and spin dipoles** [Submitted to *Advanced Electronic Materials*].

We have discovered that the magnetic properties of intermolecular charge-transfer states in electric-magnetic nano-composite can be adjusted by photoexcitation though varying the Coulomb interaction between intermolecular charge-transfer states and magnetic spin dipoles. Fig. 5 depicts an interesting phenomenon of narrowing line-shape and increasing amplitude of magnetocapacitance with increasing photoexcitation intensities. As a consequence, this straightforward phenomenon clarify a unique way to tune the magnetic properties through

changing the interaction between intermolecular charge-transfer states and magnetic spin dipoles with varied photoexcitation intensities.

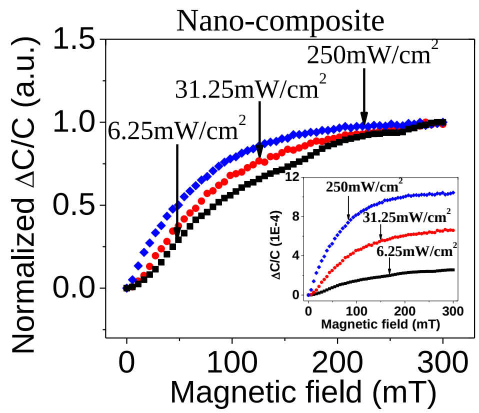


Fig. 5 Magnetocapacitance in electric-magnetic nano-composite under different photoexcitation intensities.

3. Discovery: New approach to realize optically tunable plasmonics [to be publsiehd]

We have discovered a new mechanism to separately control the magnetized charge-transfer states and photo-induced charge-transfer states through the coupling interaction between them. Fig. 6 shows the coupling interaction between magnetized charge-transfer states and photo-induced charge transfer states becomes stronger with the decreasing distance. This new phenomenon on one hand provides a unique way to magnetically control the photo-induced charge-transfer states. On the other hand, it predicts a method to optically tune the magnetic plasmonic response. Consequently, this new finding affords a new approach to coupling the electric, optic and magnetic properties for developing new metamaterials.

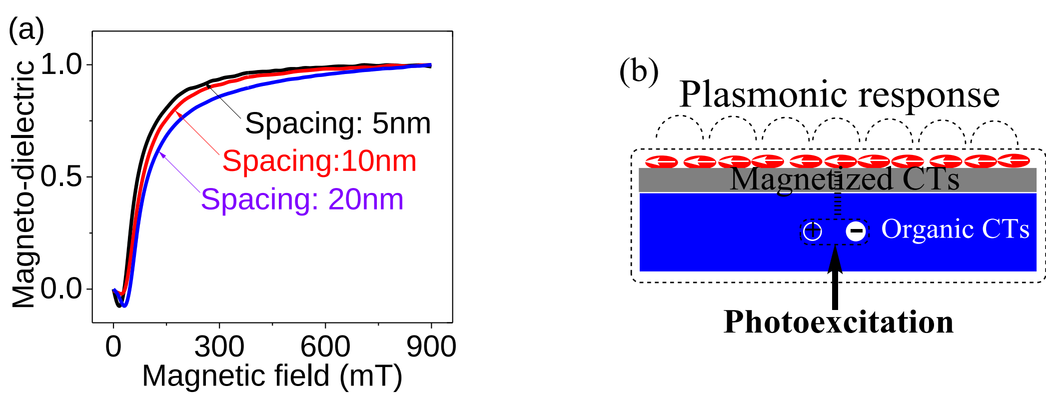


Fig. 6 (a) Magneto-dielectric property to show the coupling interaction between magnetized charge-transfer states and photo-induced charge transfer states. (b) Schematic for illustrating excitons-based plasmonics with optical tuning.

4. **New mechanism to develop magneto-optic properties by combining Hall effects with spin radicals** [*Adv. Mater*. 23, 2216-2220, 2011]

We have found a new mechanism to develop magneto-optic properties by combining Hall effects with spin radicals. This new mechanism has led to huge magneto-optic function based on organic spin radicals. Fig. 7 presents that the electroluminescence can be significantly changed up to > 400 % by a magnetic field at room temperature and low field (< 700 mT). This experimental discovery indicates a new mechanism to develop magneto-optic properties in liquid states.

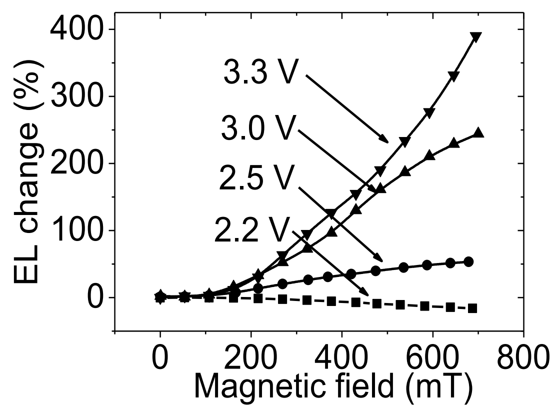


Fig.7 Electroluminescence from radical pairs as a function of magnetic field in triplet tris(2, 2'-bipyridyl) ruthenium(II)–tripropylamine.

5. **Discovery: Optically induced ferromagnetic properties from radical pairs** [*Scientific report*s 5, 2015]

We have discovered a new phenomenon that electrogenerated chemiluminescence can produce a magnetic property after removing the applied magnetic field. Fig. 8 shows an abnormal magnetic field effect on electrogenerated chemiluminescence: the electrogenerated chemiluminescence can still present a change even without a magnetic field. This unexpected phenomenon suggests that the activated charge-transfer [Ru(bpy)33+…TPrA•] complexes may become magnetized in magnetic field and experience a long magnetic relaxation after removing magnetic field. Therefore, this new discovery presents a new way to manipulate the magnetic property for developing new metamaterials.

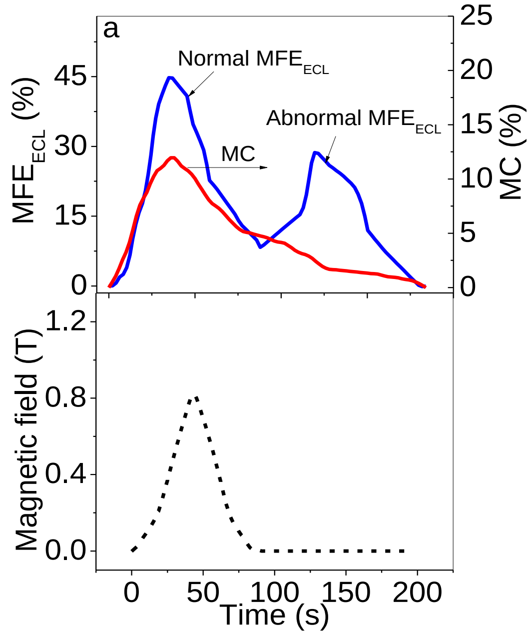


Fig. 8 (a) Magnetic field effect on electrogenerated chemiluminescence and magnetocurrent showing the magnetized charge-transfer states.

II. Thin-film based polymer thermoelectric devices

This research task has made the following five accomplishments including:

1. Rational design on polymer/conductor interface to develop high Seebeck effect based on vertical conductor/polymer/conductor thin-film devices [*Adv. Mater.* 23, 4120-4124, 2011]

We have discovered a new strategy to separately control electrical and thermal conductions by combining low thermal-conducting polymer and high electric-conducting metal in hybrid metal/polymer/polymer thin-film design. We can see in Fig. 9 that the hybrid Al/doped polypyrrole/Al thin-film device can exhibit a high Seebeck coefficient (100 ~ 200 μV/K). This high Seebeck coefficient implies a high-electric conduction and a low-thermal conduction existed in the Al/doped polypyrrole/Al thin-film device. In particular, this discovery presents a new design to separately control electric and thermal conductions by polymer/metal interface.

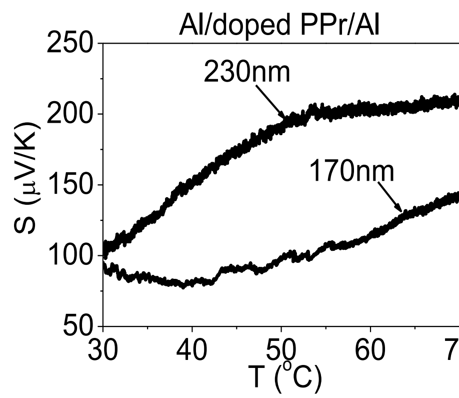


Fig. 9 Seebeck coefficients

2. New driving force of temperature-dependent surface polarization to cooperatively enhance Seebeck effect and electrical conductivity in vertical multilayer organic thin-film devices [*Phys. Chem. Chem. Phys.* 16, 22201-22206, 2014]

We have explored a new mechanism to develop Seebeck effects by using temperature-dependent surface polarization based on vertical multi-layer thin-film devices (Al/P3HT:PCBM/Al, & Al/MoO_3/P3HT:PCBM/Al). Here, the temperature-dependent surface polarization functions as an additional driving force, as compared with the traditional driving force from entropy difference, to diffuse the charge carriers under temperature difference towards the development of Seebeck effects. We have demonstrate simultaneously enhanced Seebeck coefficient and electrical conductivity by using dielectric interface through the temperature-dependent surface polarization to diffuse charge carriers in the Al/MoO_3/P3HT:PCBM/Al thin-film device (Fig. 10). This temperature-dependent surface polarization provides a new mechanism allowing a co-operative relationship between Seebeck coefficient and electrical conductivity.

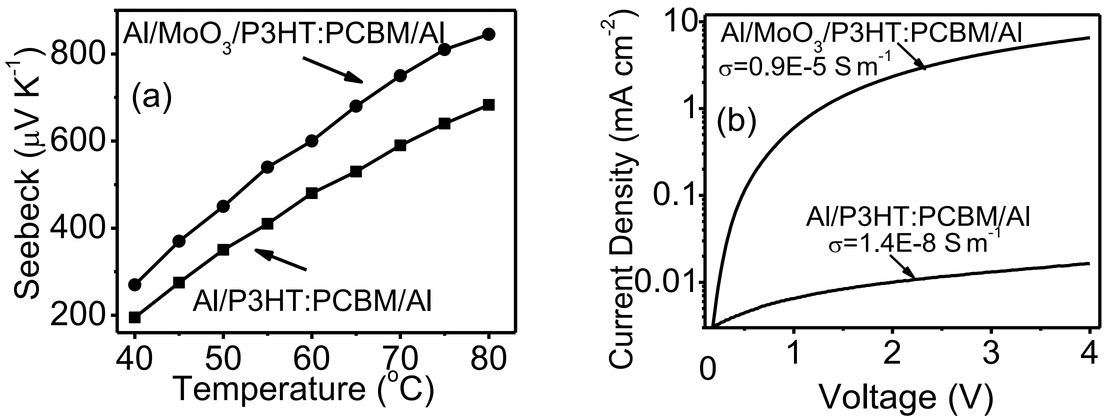


Fig. 10 (a) Seebeck coefficients in dark condition. (b) Electric conduction in dark condition.

3. Dual functions of Seebeck and cooling effects in organic thin-film devices [Submitted]

Here we have explored the possibilities of using temperature-dependent surface polarization as a new thermoelectric driving force to solve the conflicting requirement between electrical and thermal conductions in developing dual Seebeck and cooling effects based on the hybrid organic/inorganic Au/P(VDF-TrFE)/MoO_3/ITO thin-film device (Fig. 11). On one hand, the temperature-dependent surface polarization can lead to a temperature-dependent electrical field to drift charge carriers from high to low-temperature surface, generating a large Seebeck effect. On the other hand, the temperature-dependent surface polarization can absorb heat at the Au/organic interface through charge-phonon coupling by thermionic injection mechanisms when the charge carriers are injected upon applying an electrical bias, leading to a cooling effect. Essentially, the temperature-dependent surface polarization provides a mechanism to develop dual Seebeck and cooling effects through charge-phonon coupling based on thin-film electrode/organic/electrode devices.

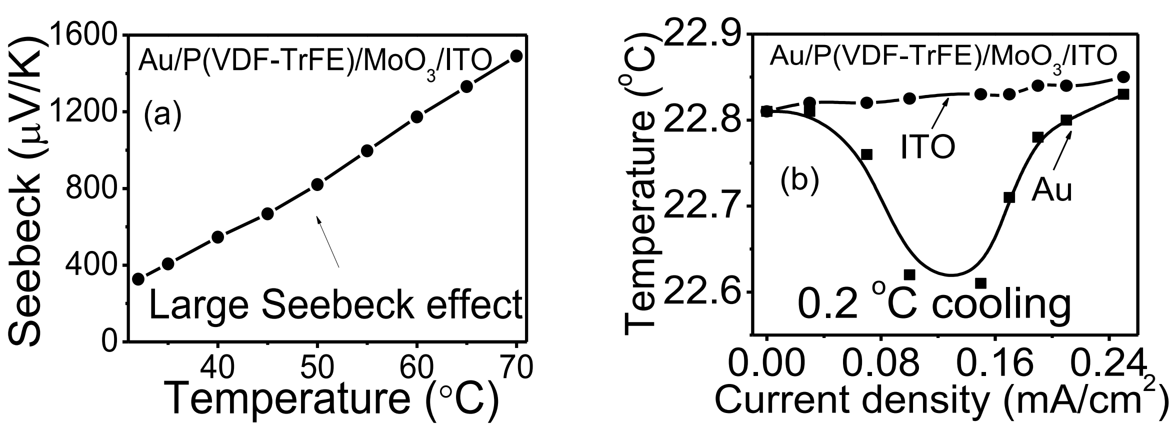


Fig. 11 (a) Seebeck coefficients. (b) Cooling effects with small injection currents.

4. Excited-states based Seebeck effect with decoupled three key parameters of Seebeck coefficient, electrical conductivity, and thermal conductivity [*J. Phys. Chem. C*, 117, 10264-10269, 2013]

Recently, we have discovered a new mechanism to further separately control electrical and thermal conductions by using photoexcitation. *Traditionally*, doping has been largely used to control thermoelectric functions. But, doping can cause conflicting phenomena: increasing electrical conductivity but decreasing Seebeck effect. This leads to a big challenge for simultaneously increasing electrical conductivity and Seebeck coefficient to enhance thermoelectric functions. Now, we have discovered that photoexcitation can lead to an increased Seebeck effect in the organic semiconducting system (MEHPPV) (Fig. 12). The observed increased Seebeck effect implies that using photoexcited states can develop a separate control on electrical and thermal conductions towards the development of high-efficiency thermoelectric devices. Essentially, excited states can provide three unique properties to develop Seebeck effect. First, the excited-states can generate high electrical conductivity; second, the excited-states can lead to tunable electron-phonon coupling; third, the excited states can provide a mechanism of phonon-trapping to trap thermal transport in bulk polymer films during charge transport.

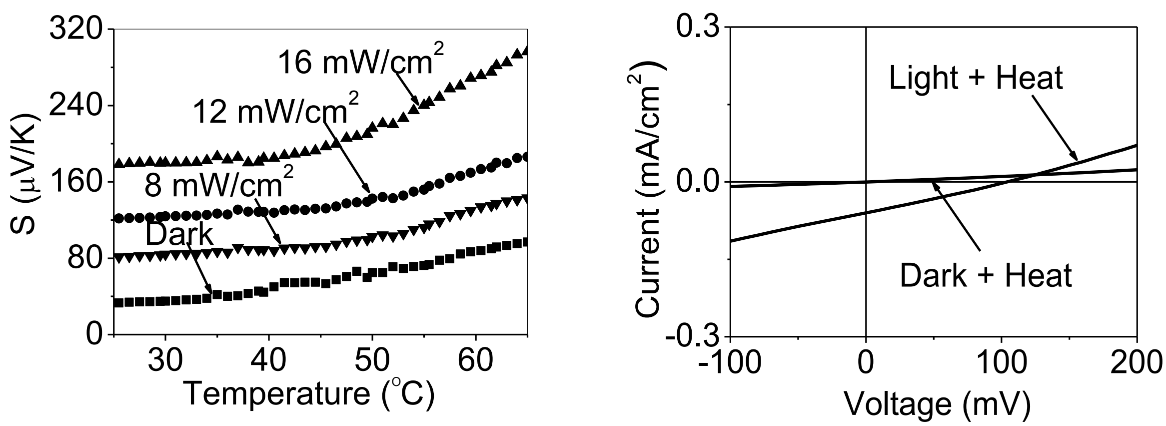


Fig. 12 (a) Seebeck coefficients for photoexcitation and dark conditions. (b) Electric conductions for photoexcitation ($16mW/cm^2$) and dark conditions. The system is based on ITO/MEH-PPV/Au devices.

5. New mechanism to generate magneto-Seebeck effect by applying Hall effect on organic thin-film devices [Submitted]

Hall effect can generate magneto-transport phenomenon in organic thin-film devices, and vertical organic thin-film devices can lead to large Seebeck effect. Therefore, combination of Hall effect and vertical organic thin-film devices can lead to a new mechanism to generate magneto-Seebeck effect. Here we have discovered giant magnetic field effects on Seebeck coefficients by applying Hall effect on vertical multi-layer ITO/PEDOT:PSS/Au thin-film

devices (Fig. 13). This discovery demonstrates a magnetic approach to control the thermoelectric properties in organic thin-film devices.

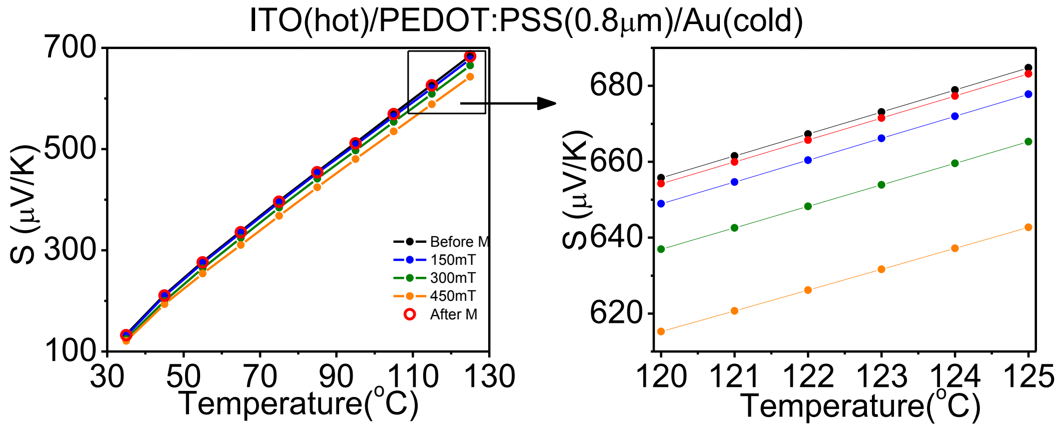


Fig. 13 Seebeck coefficient as a function of temperature under different magnetic field when magnetic field is perpendicular to temperature gradient.

Personnel Supported:

1. Dr. Lei He with full support
2. Dr. Dehua Hu with full support
3. Ph.D student Liang Yan with full support
4. Ph.D student Huidong Zang with full support
5. Ph.D student Mingxing Li with full support
6. Ph.D student Qing Liu with full support

Publication preparation from July 01 2011 to December 31 2014

1. Magneto-Optical Studies on Spin-Dependent Charge Recombination and Dissociation in Perovskite Solar Cells
   Yu-Che Hsiao, Ting Wu, Mingxing Li, and Bin Hu
   Advanced Materials, DOI: 10.1002/adma.201405946, 2015
2. Abnormal Magnetic Field Effects on Electrogenerated Chemiluminescence
   Haiping Pan, Yan Shen, Hongfeng Wang, Lei He, Bin Hu*
   Scientific Reports, DOI: 10.1038/srep09105, 2015
3. Changing the sign of exchange interaction in radical pairs to tune magnetic field effect on electrogenerated chemiluminescence
   Haiping Pan, Yan Shen, Lin Luan, Kai Lu, Jiashun Duan, and Bin Hu
   J. Phys. Chem. DOI: 10.1021/acs.jpcc.5b01541, 2015
4. Dynamic Coupling between Electrode Interface and Donor/Acceptor Interface via Charge Dissociation in Organic Solar Cells at Device-Operating Condition
   Ting Wu, Yu-Che Hsiao, Mingxing Li, Nam-Goo Kang, Jimmy W. Mays, Bin Hu*
   J. Phys. Chem. C, DOI: 10.1021/acs.jpcc.5b00082, 2015
5. Optically-Tunable Magneto-Capacitance Phenomenon in Organic Semiconducting Materials Developed by Electrical Polarization of Intermolecular Charge-Transfer States
   Lei He, Mingxing Li, Augustine Urbas, and Bin Hu*
   Advanced Materials, **26**, 3956, 2014
6. Changing Line-Shape in Magnetic Field Effects through Interactions between Excited States in Organic Semiconducting Materials
   Lei He, Mingxing Li, Augustine Urbas, and Bin Hu*
   Phys. Rev. B **89**, 155304, 2014
7. Optically tunable spin-exchange energy at donor:acceptor interfaces in organic solar cells
   Mingxing Li, Hongfeng Wang, Lei He, Huidong Zang, Hengxing Xu, and Bin Hu
   Appl. Phys. Lett. **105**, 023302, 2014
8. Inter-triplet spin-spin interaction effects on inter-conversion between different spin states in intermediate triplet-triplet pairs towards singlet fission
   Xianfeng Qiao, Lin Luan, Yuchun Liu, Zhigang Yu, and Bin Hu

Organic Electronics, **15**, 2168, 2014

9. Light induced structural change in Iridium complexes studied by electron spin resonance
A. Batagin-Netol, A.P. Assis, J.F. Lima , C.J. Magon , L. Yan , M. Shao, B. Hu, and C.F.O. Graeff
Journal of Physical Chemistry-A, **118**, 3717, 2014
10. Magneto-Dielectric Effects Induced by Optically-Generated Intermolecular Charge-Transfer States in Organic Semiconducting Materials
Huidong Zang, Liang Yan, Mingxing Li, Lei He, Zheng Gai, Ilia Ivanov, Min Wang, Long Chiang, Augustine Urbas, and Bin Hu*,
Scientific Reports, DOI: 10.1038， 2013
11. Precise Structural Development and Its Correlation to Function in Conjugated Polymer: Fullerene Thin Films by Solvent Annealing
Huipeng Chen, Shen Hu, Huidong Zang, Bin Hu, and Mark Dadmun
Advanced Functional Materials, **23**, 1701-1710, 2013
12. Spin Radicals Enhanced Magnetocapacitance Effect in Intermolecular Excited States
Huidong Zang, Jianguo Wang, Mingxing Li, Lei He, Zitong Liu, Deqing Zhang, and Bin Hu
J. Phys. Chem. C, **117**，14136-14140， 2013
13. Effects of Purity on the Electro-Optical Properties of Single Wall Nanotube-Based Transparent Conductive Electrodes
Matthew Garret, Ilia N. Ivanov, David Geohegan, Bin Hu
Carbon, **64**, 1-5, 2013
14. Enhancing Seebeck Effects by Using Excited States in Organic Semiconducting Polymer MEH-PPV Based on Multi-layer Electrode/Polymer/Electrode Thin-Film Structure
Ling Xu, Yuchun Liu, Matthew P.Garrett, Bingbing Chen, and Bin Hu
Journal of Physics Chemistry C, **117**, 10264, 2013
15. Triplet-Charge Annihilation versus Triplet-Triplet Annihilation in Organic Semiconductors
Ming Shao, Liang Yan, Li Mingxing, Ivanov Ilia, and Bin Hu*
Journal of Materials Chemistry C, **1**, 1330-1336, 2013
16. High Seebeck Effects from Conducting Polymer: Poly(3,4-ethylenedioxythiophene): Poly(styrenesulfonate) Based Thin-Film Device with Hybrid Metal/Polymer/Metal Architecture
Michael Stanford, Hsin Wang, Ilia Ivanov, and Bin Hu*
Applied Physics Letters **101**, 173304, 2012
17. Doping Effects on Internally Coupled Seebeck Coefficient, Electrical and Thermal Conductivities in Aluminum-Doped TiO_2
Ling Xu, Matthew P.Garrett, and Bin Hu
Journal of Physical Chemistry C, **116**, 13020-13025, 2012
18. "Magnetocurrent of Charge-Polarizable C_{60}-Diphenylaminofluorene Monoadduct-Derived Magnetic Nanocomposites"

Liang Yan, Min Wang, N.P. Raju, Arthur Epstein, Loon-Seng Tan, Augustine Urbas, Long Y. Chiang, Bin Hu*
J. Am. Chem. Soc. **134**, 3549-3554, 2012

19. "Changing Inter-molecular Spin-Orbital Coupling for Generating Magnetic Field Effects in Phosphorescent Organic Semiconductors"
Liang Yan, Ming Shao, Carlos F. O. Graeff, Ivo Hummelgen, Dongge Ma, Bin Hu
Appl. Phys. Lett. **100**, 013301, 2012
20. The impact of controlled solvent exposure on the morphology, structure and function of bulk heterojunction solar cells
Raghavendra Hegde, Nathan Henry, Ben Whittle, Huidong Zang, Bin Hu, Jihua Chen, Kai Xiao, Mark Dadmun
Solar Energy Materials and Solar Cells, **107**, 112-124, 2012
21. "High Seebeck Effects from Hybrid Metal/Polymer/Metal Thin-Film Devices"
Liang Yan, Ming Shao, Hsin Wang, Doug Dudis, Augustine Urbas, and Bin Hu*
Adv. Mater. **23**, 4120-4124, 2011
22. "Intra-Molecular "Donor-Acceptor" Interaction Effects on Charge Dissociation, Charge Transport, and Charge Collection in Bulk-Heterojunction Organic Solar Cells"
Huidong Zang, Yongye Liang, Luping Yu,* and Bin Hu*
Adv. Energ. Mater. **1**, 923, 2011
23. "Giant Magnetic Field Effects on Electroluminescence in Electrochemical Cells",
Ming Shao, Liang Yan, Ilia Ivanov, Bin Hu*,
Adv. Mater. **23**, 2216-2220, 2011.
24. "Effects of single walled carbon nanotubes on the electroluminescent performance of organic light-emitting diodes", Ming Shao, Matthew Garrett, Xinjun Xu, Ilia Ivanov, Stanislaus Wong, and Bin Hu*,
Organic Electronics, **12**, 1098-1102, 2011.
25. "Electrical dipole-dipole interaction effects on magnetocurret in organic phosphorescent materials",
Ming Shao, Yanfeng Dai, Dongge Ma, and Bin Hu
Appl. Phys. Lett. **99**, 073302, 2011
26. "Magnetoconductance responses in organic charge-transfer-complex molecules"
Tsung-Hsun Lee, Jhen-Hao Li, Wei-Shun Huang, Bin Hu, J. C. A. Huang, Tzung-Fang Guo, and Ten-Chin Wen
Appl. Phys. Lett. **99**, 0733097, 2011

Interactions and Transitions:

a. Presentations at Conferences

Invited Presentation from July 01 2011 to December 31 2014

(1) Magneto-Optical Studies on Organic and Perovskite Solar Cells
Bin Hu

Asian Conference on Organic Electronics, National Cheng Kung University, Tainan, Taiwan, November 12-15, 2014

(2) Magneto-Dielectric Effects Generated by Charge-Transfer States in Organic Semiconductors
Bin Hu
5th Topical Meeting on Spins in Organic Semiconductors, Himeji, Japan, October 14-17, 2014

(3) New Magnetic Field Effects in Organic Semiconductors
Bin Hu
2014 International Symposium on Materials for Enabling Nanodevices, National Cheng Kung University, Tainan, Taiwan, September 03-06, 2014

(4) Magneto-optic properties in organic materials
Bin Hu
AOARD conference on magnetic nanomaterials, University of Maryland, June 16-17, 2014

(5) Organic spintronics, organic solar cells, and organic thermoelectrics
Bin Hu
E-MRS, Lille, France, May 26-30, 2014

(6) Magneto-optic properties in organic materials
Bin Hu
US-Taiwan Air Force Conference, Hualien, Taiwan, May 13-15, 2014

(7) Magneto-optic studies of photovoltaic processes at D:A interface and electrode interface in organic solar cells
Bin Hu
Indo-US Joint Workshop on Organic Solar Cells, Kanpur, India, March 20-22, 2014

(8) Interface enhanced photovoltaic and Seebeck effects in organic solar cells and thermoelectric devices
Bin Hu
ACS Annual Meeting, Dallas, TX, March 16, 2014

(9) Multiferroic Effects from Intermolecular Excited States in Organic Semiconductors
Bin Hu
Brazil-MRS meeting, Campos do Jordao, September 30 – October 04, 2013

(10) Magneto-Optic, Magneto-Electric, and Magneto-Thermoelectric Effects in Organic Semiconductors
Bin Hu
BES Program Review for the CNMS at Oak Ridge National Laboratory, September 24-26, 2013

(11) Organic Thin-Film Thermoelectric Devices
Bin Hu
Flexible Thermoelectric Workshop organized by AFOSR, Arlington, VA, July 09-10, 2013

(12) Effects of Intermolecular and Dielectric-layer Interfaces on Internal Photovoltaic Processes in Organic Solar Cells
Bin Hu

Indo-US Joint Workshop on Organic Solar Cells, National Reviewable Energy Laboratory, Golden, Co, June 24-25, 2013

(13) Magneto-optical Studies on Internal Photovoltaic Processes in Organic Solar Cells
Bin Hu
2013 TechConnect World, National Innovation Summit and National SBIR Conference, Gaylord Hotel, National Harbor, Maryland, May 13-16, 2013

(14) Magneto-Dielectric Functions Developed by Intermolecular Excited States
Bin Hu
MRS Meetings, San Francisco, CA, April 01-05, 2013

(15) Departmental Seminar: Organic Spintronics
Bin Hu
National Taiwan University, Taipei, Taiwan, December 11, 2012

(16) Workshop on Organic Spintronics
Bin Hu
Intermolecular Excited States-Based Organic Spintronics
National Cheng Kung University, Tainan, Taiwan, December 06-07, 2012

(17) Effects of Intermolecular and Dielectric-layer Interfaces on Internal Photovoltaic Processes in Organic Solar Cells
Bin Hu
International Symposium on Organic and Dye-Sensitized Solar Cells 2012 (IS-OPVDSC 2012), Taipei, Taiwan, November 24-29, 2012

(18) Electric-Magnetic Coupling in Organic Sintronics
Bin Hu
9th National Conference on Organic Solids Electronics, Yangzhou, China, November 10-12, 2012

(19) Magneto-optical studies on internal photovoltaic processes in organic solar cells
Bin Hu
Workshop on key scientific and technological issues for development of next-generation organic solar cells
Arlington, VA, September 20 – 21, 2012

(20) Multi-Ferroic Functions Developed by Inter-molecular Excited States
Bin Hu
4th Topical Meeting on Spintronics in Organic Semiconductors, London, UK, September 10 – 14, 2012

(21) Excited States-Based Organic Spintronics
Bin Hu
International Workshop on Novel Nano-Magnetic and Multifunctional Materials 2012
Seoul, Korea, June 11-14, 2012

(22) Magneto-Optical Studies of Internal Photovoltaic Processes in Organic Solar Cells
Bin Hu
Departmental seminar at Department of Materials Science and Engineering, University of Florida, Gainesville, FL, April 04, 2012

(23) Organic Molecular Metamaterials
Bin Hu
Organic Metamaterials Workshop, Army Research Laboratory, March 02, 2012

(24) Characterization and Understanding on Internal Photovoltaic Processes in Organic Solar Cells
Bin Hu
International Photonics Conference – 2011, Tainan, Taiwan, December 07-08, 2011

(25) Organic Spintronics: Magnetic Field Effects
Bin Hu
International Symposium on Organic Dye Sensitized Solar Cells, Tainan, Taiwan, December 08-10, 2011

(26) The Role of Inter-molecular Electron-Hole Pairs in Magnetic Field Effects in Organic Materials,
Bin Hu
61st Annual Meeting of Japan Coordination Chemistry Society, Okayama, Japan, September 17-19, 2011

(27) Characterization and Understanding on Charge Dissociation, Transport, Collection in Organic Solar Cells
Bin Hu
Workshop on Sustainable Energy Future: Focus on Organic Photovoltaics, Oak Ridge National Laboratory, September 21 – 23, 2011

(28) Electromagnetic and Thermoelectric Responses from Inter-molecular Excited States: Radicals Pairs
Bin Hu
8th US-Taiwan NanoScience Workshop, Seattle, Washington, April 05-06, 2011

b. *Consultative and advisory functions*

None.

c. *Transitions*

None.

New Discoveries

Four experimental discoveries have been made. They include:

(1) New strategy to couple semiconducting π electrons and magnetic d electrons for development of molecular metamaterials
(2) New mechanism to use intermolecular excited states for realizing electric-magnetic coupling towards development of molecular metamaterials
(3) New method to use spin radicals for realizing electric-magnetic coupling towards radicals-based metamaterials
(4) New mechanism to develop significant magneto-optic properties by combining Hall effect with spin nradicals
(5) New strategy to separately control electrical and thermal conductivities by using interfacial polarization

Honors/Awards:

Research Achievement Award – April 2014
College of Engineering
University of Tennessee

Research Fellow Award – April 2012
College of Engineering
University of Tennessee

1.

1. Report Type

Final Report

Primary Contact E-mail

Contact email if there is a problem with the report.

bhu@utk.edu

Primary Contact Phone Number

Contact phone number if there is a problem with the report

865-974-3946

Organization / Institution name

The University of Tennessee

Grant/Contract Title

The full title of the funded effort.

Exploring Electrical and Magnetic Resonances from Coherently Correlated Long-Lived Radical Pairs towards Development of Negative Refractive-Index materials

Grant/Contract Number

AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-11-1-0082

Principal Investigator Name

The full name of the principal investigator on the grant or contract.

Dr. Bin Hu

Program Manager

The AFOSR Program Manager currently assigned to the award

Dr. Charles Lee

Reporting Period Start Date

06/01/2011

Reporting Period End Date

12/31/2014

Abstract

The research efforts have made following major breakthroughs:
1. Developed new strategy to couple pi-d electrons for the development of molecular metamaterials [J. Am. Chem. Soc. 134, 3549, 2012]
2. Explored new mechanism to utilize intermolecular excited states for realizing electric-magnetic coupling towards developing molecular metamaterials [Adv. Mater. 23, 2216, 2011]
3. Developed new method to use radicals for electric-magnetic coupling towards radicals-based metamaterials [Adv. Mater 26, 3956, 2014]
4. Discovered a novel mechanism to generate magneto-optic properties by establishing spin-exchange interaction in electron-hole pairs in ferroelectrically semiconducting materials [Advanced Materials, DOI: 10.1002/adma.201405946, 2015]
5. Developing new strategy to separately control electrical and thermal conductivities by using interfacial polarization [Adv. Mater. 23, 4120, 2011]

Distribution Statement

This is block 12 on the SF298 form.

Distribution A - Approved for Public Release

Explanation for Distribution Statement

If this is not approved for public release, please provide a short explanation. E.g., contains proprietary information.

SF298 Form

Please attach your SF298 form. A blank SF298 can be found here. Please do not password protect or secure the PDF The maximum file size for an SF298 is 50MB.

Final report-298-Bin Hu.pdf

Upload the Report Document. File must be a PDF. Please do not password protect or secure the PDF . The maximum file size for the Report Document is 50MB.

Final Performance Report-04-12-2015-Bin Hu-submitted.pdf

Upload a Report Document, if any. The maximum file size for the Report Document is 50MB.

Archival Publications (published) during reporting period:

Changes in research objectives (if any):

Change in AFOSR Program Manager, if any:

Extensions granted or milestones slipped, if any:

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

E-mail user

Apr 16, 2015 14:26:17 Success: Email Sent to: bhu@utk.edu